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INTERCOMPARISON OF SNOW COVER AND SNOW MASS IN NORTH AMERICA FROM GENERAL CIRCULATION MODELS AND REMOTE SENSING

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1. INTRODUCTION

General circulation models (GCMs) are essential tools for studies of the sensitivity of climate to a variety of processes, and for predicting the magnitude, timing and spatial distribution of regional and global climate and climate changes. Regardless of how sophisticated the models are, realistic results cannot be assured unless they are used with care and tested against results from observed data or other available data sets.

When there is a high degree of confidence that land surface data sets such as snow cover and snow depth are reliable, they can then be used to validate the performance of the GCMs. Snow in particular is a good diagnostic for verification since, at least during accumulation, it is not diverted into streamflow or groundwater and so can be more easily accounted for than rainfall, for instance.

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In this study how GCMs perform at continental scales will be quantitatively determined. Model results from several GCMs will be intercompared for North American, and the GCM outputs will also be compared with remote sensing (passive microwave and visible data) results. Quantifying the ability of GCMs to represent the global hydrologic cycle is important. This is the thrust of the Atmospheric Modeling Intercomparison Project (AMIP) which is using a ten-year period to intercompare model output from more than two dozen GCMs.

2. DATA SETS

2.1. GCMs

A number of modeling groups have agreed to share their GCM data for this study. The United Kingdom Meteorological Office (UKMO) in Bracknell, England: the Canadian Climate Centre in Downsview, Ontario; The National Center for Atmospheric Research in Boulder, Colorado; the Max Planck Institute (MPI) for Meteorology in Hamburg, Germany; the Goddard Institute for Space Studies, in New York; and the Goddard Space Flight Center (GSFC) in Greenbelt, MD have all provided snow mass and snow cover data. Most all of the available GCMs formulate snow in a similar manner. Precipitation falls as snow when the temperature of the lowest atmospheric level is below 0 C (Cattle, 1991). Snow thickness is calculated as a balance of snowfall, melting and sublimation (Cess et al., 1991). However, differences in factors such as physical parameterizations, grid size, and albedo result in different values of snow extent and snow mass. With the models, prediction of snow conditions is not hindered by the spectral limitations of remote sensors.

2.2. Passive Microwave Data

Since November 1978, the Scanning Multichannel Microwave Radiometer (SMMR) instrument on the Nimbus-7 satellite and the Special Sensor Microwave Imager (SSM/I) on DMSP satellite have been acquiring passive microwave data which can be used to estimate snow extent and snow depth. The algorithm developed by Chang et al. (1987) uses the difference between the SMMR 37 GHz and 19 GHz channels to derive a snow depth-brightness temperature relationship for a uniform snow field. This is expressed as follows:

$$SD = 1.59 * (T_B 18H - T_B 37H)$$

where SD is snow depth in cm, H is horizontal polarization, and 1.59 is a constant derived by using the linear portion of the 37 and 18 GHz responses to obtain a linear fit of the difference between the 18 GHz and 37 GHz frequencies. If the 18 GHz T_B is less than the 37 GHz T_B, the snow depth is defined to be zero.

2.3. NOAA Visible Data

Since 1966, the National Oceanic and Atmospheric Administration (NOAA) has prepared a weekly snow and ice boundary chart for the Northern Hemisphere. Monthly mean snow cover charts have been constructed from the weekly charts by deriving a subjective average of the weekly chart boundaries of each month. The areal extent of continental snow cover within this average monthly snow cover boundary is then measured and recorded. Each chart is the latest cloud-free snow observation of the particular area of the world.

The NOAA data set is subject to inaccuracies in locating snowlines due to prolonged periods of cloudiness in some areas and to analyst error in interpreting snow-free versus snow-covered terrain. However, the NOAA data are judged to be the most reliable of the available snow cover data sets.

2.4. Snow Depth Climatology

The U.S. Air Force Environmental Technical Applications Center (USAF/ETAC) at Scott Air Force Base in Illinois has assembled a global snow depth climatology (SDC) that is fully documented and is capable of being updated. This global snow depth climatology uses a mesh reference grid that divides each hemisphere into 64 equal boxes. Each base is divided into 4096 grid points that are about 46 km apart. For each month, every box and every grid point a snow depth value (taken to be representative of the middle of the month) is assigned based on results primarily from climatological records, literature searches, surface weather synoptic reports, and data obtained at snow course sites.

As with the NOAA data, this data set is not without sources of error. In a number of countries, summarized snow depth values are not always available to construct a snow climatology with even a fair degree of confidence. Nevertheless, because in many cases the snow depths have been directly observed, these data are deemed to be the most reliable of the limited snow depth data sets available.

For the purposes of this study North America encompasses all land areas between 10° and 170°W longitude. However, ice sheets are not counted in the snow cover calculations since the emphasis in this study is seasonal snow only. Thus Greenland is excluded as are islands such as Spitsbergen and some of the islands of the Canadian Archipelago.

3. RESULTS

The UKMO (UK) model, the MPI model and the GSFC (G1) model are run for the years 1979-1988 which is the time frame of the AMIP integrations. Due to space limitations these are the only models discussed in this paper. Although results from the other modeling groups mentioned above are similar. During these model simulations, sea ice extent and sea surface temperatures are prescribed and updated each month during the ten-year period based on observations. Monthly average snow output in terms of snow cover and snow mass are generated for the 1979-1988 period. The AMIP period is concordant with the SMMR record (1978-1987), and thus intercomparison between the AMIP modeled snow results and the passive microwave snow estimates are of particular interest.

Comparisons for a single year (1987) between the SMMR snow data and data from the UKMO Hadley model (year 1) demonstrated that GCMs were capable of representing observed snow conditions (Foster et al., 1993). The intent now is to see how snow output from different GCMs for a number of years, compares to snow conditions extracted from climatological data and from remotely-sensed observations.

NOAA visible data were used as the standard to compare the modeled snow extent output and the passive microwave estimates. For snow mass measurements, the US Air Force snow depth climatology was used as the base line to compare modeled snow mass and microwave derived estimates of snow mass. Snow mass is the derived snow depth times a specified density. For example, the density for the SMMR and USAF snow climatology is 0.3 g/cm^3 and for the Hadley and UK models it is 0.25 g/cm^3. The snow mass is given in units of 10^{13} kilograms, and the snow extent is given in units of 10^6 square kilometers. Snow extent in the area covered by at least a thickness of 1 mm of snow for the model data and approximately 1 cm for the NOAA data. Results are presented in Tables 1 and 2. Note, in the tables the average annual percentage difference (Jan-Dec) excludes data from Jun-Sep.

3.1. North American Snow Cover

Comparing NOAA measurements of North American snow cover to SMMR observations shows that SMMR underestimates the NOAA values for each month (Table 1). Spring is the season when the percentage differences are smallest. SMMR underestimates the NOAA values by 7.1% in March and 6.8% in April. February and March differences are similar (7.4 and 6.7%, respectively). The largest percentage differences, excluding the summer months of June through September, occur in October and November when SMMR underestimates the NOAA values by about 10%. The average annual percentage difference is 21.3%.

As with the SMMR data, the UK model snow cover results are smaller than the NOAA values for each month. During the winter period from December through March the percentage difference between the NOAA and UK results is less than 10%. October and November are the months when the differences are greatest (31.5 and 26.4%, respectively). The average annual percentage difference is 15.0%.

The GSFC-1 model snow cover values for North America compare very favorably with the NOAA values for all months with the exception of May and October. From November through April the percentage difference between the NOAA and GSFC-1 results in less than 7%. The average annual percentage difference is 9.6%.

Snow cover results from the MPI model also compare favorably with the NOAA results. The percentage difference between the NOAA and MPI results are less than 11% from November through May, and there is only a 1% difference for the months December through February. The average annual percentage difference is 9.0%.

3.2 North American Snow Mass

Concerning North American snow mass comparisons, SMMR-derived snow mass values are considerably smaller than the SDC values (Table 2). May and June are the only months when the percentage difference was less than 40%. From November through March the percentage differences are very similar, from 53.6 to 59.0%. The average annual percentage differences, excluding June through September, is 51.7%.

The UK snow mass values for North America are larger than the SDC values every month except February. The percentage differences are negligible in January, February and March (< than 4%). In October and May however, the differences are greater than 100%. The UK snow mass values are anomalously high during the summer months with absolute differences 50 x 10^{13} kg more than the SDC values. The average annual percentage difference is 50.4%.

With the GSFC-1 results, snow mass values when compared to SDC values are smaller from September through February but larger from March through June. April is the month of greatest snow mass according to results from this model. February and March are the only months when percentage differences between the SDC and GSFC-1 values are below 20%. The largest difference occurs in May (174%). The average annual percentage difference is 58.8%.

The MPI model generally underestimates snow mass when compared to the SDC snow mass values. April and October are the only mouths where the model values are larger than the SDC values. The closest agreement between the SDC results and the MPI results occurs in February (3.8%), and May is the month when the percentage difference is largest

(39.8%). The average annual percentage difference is 21.3%.

4. DISCUSSION

One reason why passive microwave snow cover estimates are smaller than the NOAA measurements is related to the ineffectiveness of microwave radiation in providing information about shallow snow cover. When the band of snow near the southern limit of the continental snowline is sufficiently shallow (<3 cm) then the radiation upwelling from the ground may pass through the snowpack virtually unimpeded (Foster et al., 1993).

Difference in snow cover areal extent during the late fall and early spring between the NOAA, microwave and model data sets may be due to the positioning of the snowline in the boreal forests. The visible sensors on-board the NOAA satellites are unable to penetrate dense forest covers and monitor the underlying snow. With the microwave data the emissivity of trees, especially dense conifers, can overwhelm the scattering signal which results when upwelling microwave energy is redistributed by snow crystals. Thus, remotely-sensed snow observations may under-represent actual snow extent and snow mass values in forested regions. For the UK model data the consistent underestimation of snow cover is possibly due to the model physics packages, i.e., radiation, precipitation and boundary layer processes, forming snow too fár to the north of where the actual snowline should be located. All three of the models have difficulty in reliably portraying snow cover conditions in October. This is the month when snow cover first advances southward, and it appears that the models have a problem in gauging when snow expansion should begin.

The boreal forests which stretch across the northern tier of North America is perhaps the physiographic region where most of the difference occurs between the snow depth measurements based on climatological data and those based on microwave observations. The most likely reason why the microwave data underestimates snow mass has to do with the effects of vegetation above snow fields. Forests not only absorb some of the radiation scattered by snow crystals, but trees are also emitters of microwave radiation. So in forested areas the signal received by a radiometer on-board a satellite is produced by a combination of media. Generally, the denser the forest, the higher the microwave brightness temperature despite the type and condition of the media underlying the forest canopy. Furthermore, because the canopy shields the snow from direct solar radiation the deepest snow accumulate in the densest forests (Foster et al., 1993).

In general, the models produce more snow mass than the SDC data or the SMMR data. The UK model overestimates snow mass in each month, but the differences between the SDC and UK results are especially noticeable during the summer and fall. The reason for this has more to do with where snow is permitted to accumulate and melt than it does with how snow accumulates and melts. During the summer in certain preferred high altitude and high latitude locations, where there exists a perennial snow cover, such as the Alaska Range, snow is evidently accumulating faster than it is melting, and hence the modeled snow mass is an order of magnitude higher than expected.

The G1 and MPI models both considerably underestimate snow mass in the colder months even though their snow cover estimates are in line with the observed values. Whether this is due to too little precipitation occurring in these models when the temperatures are below 0° C, or whether model temperatures are too warm to allow snow to adequately accumulate or to other deficiencies in the models needs to be further investigated.

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TABLE 1

Snow Cover (10^6 Km^2)
North America (1979-1988)

	NOAA 1979-87	SMMR 1979-87	Abs Dif	Per Dif	UK	Abs Dif	Per Dif	G1	Abs Dif	Per Dif	MPI	Abs Dif	Per Dif
Jan	15.1	13.0	-2.1	13.9	14.4	-0.7	4.6	15.3	+0.2	1.3	15.0	-0.1	1.0
Feb	14.9	13.8	-1.1	7.4	13.8	-1.1	7.4	14.7	-0.2	1.3	14.8	-0.1	1.0
Mar	13.4	12.5	-0.9	6.7	12.4	-1.0	7.5	12.6	-0.8	6.0	13.9	+0.5	3.7
Apr	11.2	10.6	-0.8	7.1	9.5	-1.7	15.2	11.2	0.0	0.0	11.4	+0.2	1.8
May	7.4	6.9	-0.5	6.8	6.0	-1.4	18.9	10.4	+3.0	40.5	7.1	-0.3	4.1
Jun	4.2	3.1	-1.1	26.2	2.7	-1.5	35.7	4.4	+0.2	4.8	2.7	-1.5	35.7
Jul	1.5	0.2	-1.3	86.7	0.8	-0.7	46.7	0	-1.5	100	0.6	-0.9	60.0
Aug	0.7	0.2	-0.5	71.4	0.3	-0.4	57.1	0	-0.7	100	1.8	-1.1	157
Sep	1.4	0.7	-0.7	50.0	0.8	-0.6	42.9	0	-1.4	100	4.5	+3.1	221
Oct	5.4	2.7	-2.7	50.0	3.7	-1.7	31.5	4.6	-1.2	22.2	8.0	+2.6	48.1
Nov	11.0	5.8	-5.2	47.3	8.1	-2.9	26.4	10.9	-0.1	1.0	12.2	+1.2	10.9
Dec	13.8	9.6	-4.2	30.4	12.6	-1.2	8.7	14.4	+0.6	4.3	13.9	+0.1	1.0
Jan-Dec	8.3	6.6	21.1	21.3	7.1	14.9	15.0	8.2	10.8	9.6	8.8	11.7	9.0

TABLE 2

Snow Mass (10^{13} Kg)
North America (1979-1988)

	SDC	SMMR 1979-87	Abs Dif	Per Dif	UK	Abs Dif	Per Dif	G1	Abs Dif	Per Dif	MPI	Abs Dif	Per Dif
Jan	166	77.0	-89	53.6	167	+1	1.0	119	-47	28.3	137	-29	17.5
Feb	206	88.6	-117	56.8	198	-8	3.9	172	-34	16.5	178	-28	13.6
Mar	210	88.0	-122	58.1	211	+1	1.0	214	+4	1.9	202	-8	3.8
Apr	128	70.2	-57.8	45.1	191	+63	49.2	230	+102	79.7	176	+48	37.5
May	56.5	37.4	-19.1	33.8	138	+81.5	144	155	+98.5	174	34.0	-22.5	39.8
Jun	13.6	11.2	-2.4	17.6	85.4	+71.8	528	17.7	+4.1	30.1	8.6	-5.0	36.8
Jul	0	0.4	+0.4	-	59.5	+59.5	-	0	0	-	0.1	+0.1	-
Aug	0	0.6	+0.6	-	52.6	+52.6	-	0	0	-	0.8	+0.8	-
Sep	3.9	1.6	-2.3	59.0	53.9	+50.0	1282	0	-3.9	100	3.2	-0.7	17.9
Oct	13.1	6.8	-6.3	48.1	65.0	+14.9	114	3.2	-9.1	69.5	16.8	+3.7	28.2
Nov	50.1	20.7	-29.4	58.7	88.9	+38.8	77.4	21.6	-28.5	56.9	46.4	-3.7	7.4
Dec	115	47.2	-67.8	59.0	130	+15	13.0	65.3	-49.7	43.2	89.0	-26	22.6
Jan-Dec	80.2	56.2	514	51.7	120	457	50.4	83.2	381	58.8	74.3	176	21.3